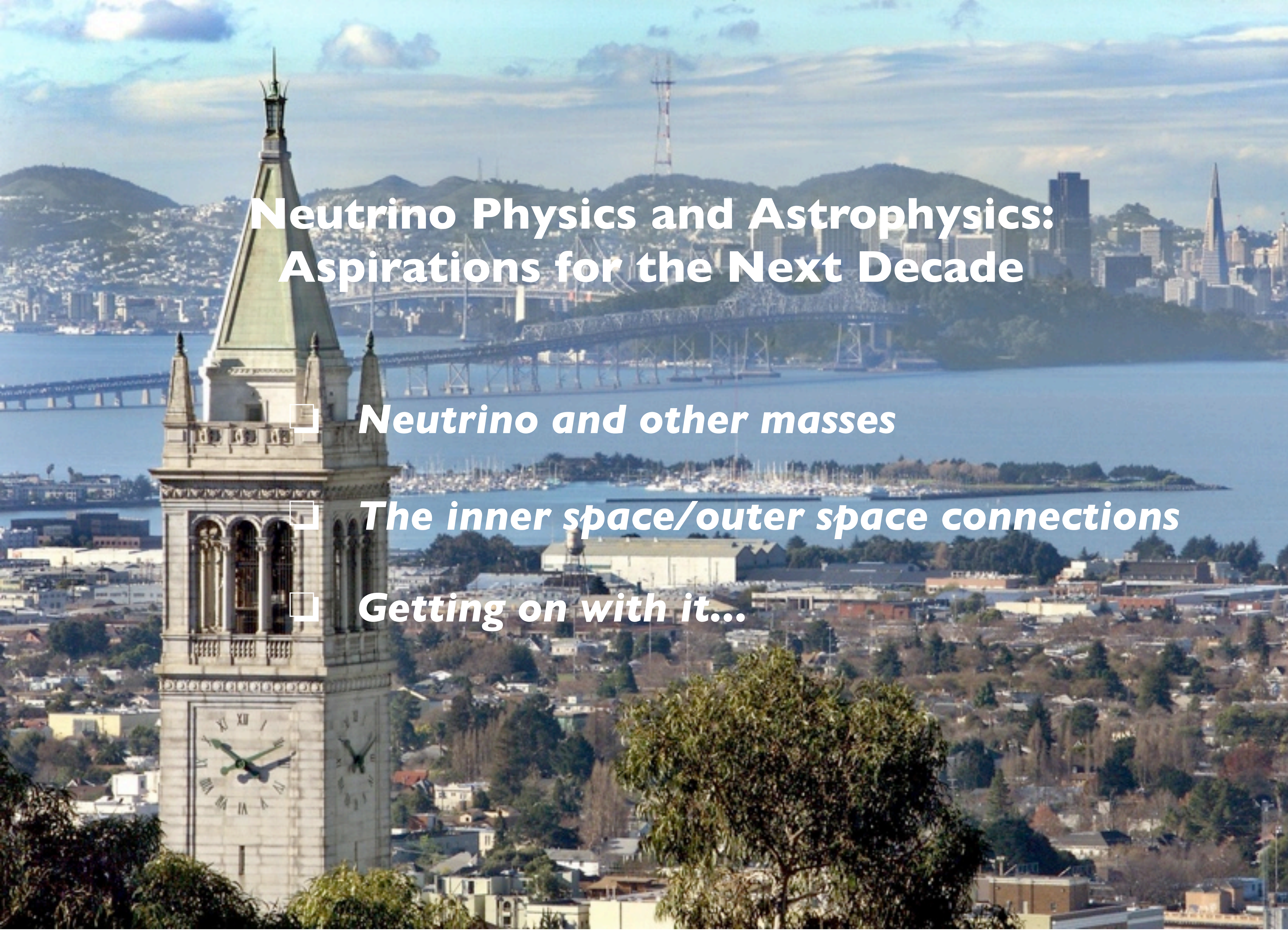


Neutrino Physics and Astrophysics: Aspirations for the Next Decade

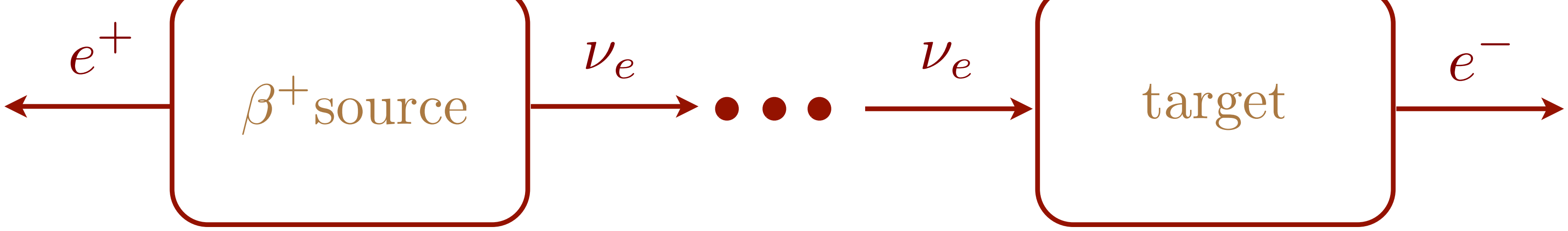
- ***Neutrino and other masses***
- ***The inner space/outer space connections***
- ***Getting on with it...***

Wick Haxton *FermiLab Wine & Cheese* *15 July 2011*

I. Neutrino mass: introduction

- the ν mass story differs from than that of other standard model fermions because
  - the scale is anomalous, an eV or lower
  - the ν has no charge or other distinguishing additive quantum number: thus are the degenerate ν and $\bar{\nu}$ coincident, orthogonal, or some admixture of these limits?

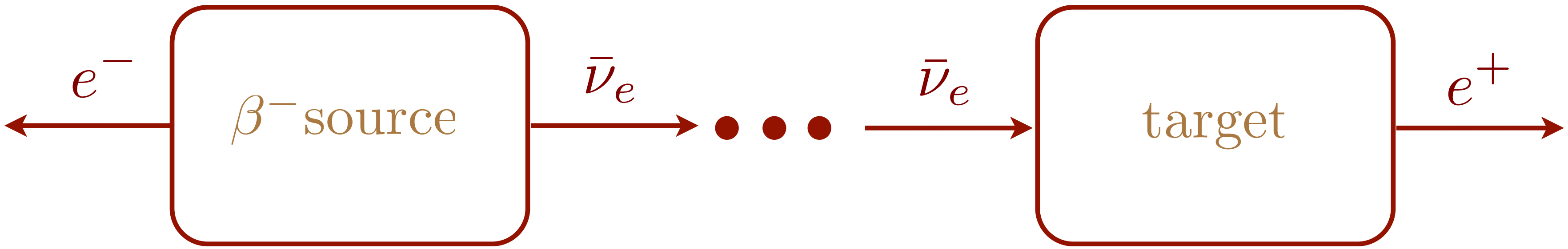
so we do an experiment:



this defines the ν_e

which is then found to produce: e^-

and a second one:



this defines the $\bar{\nu}_e$

which is then found to produce: e^+

- with these definitions of the ν_e and ν_e , they appear operationally distinct, producing different final states

- introduce a "charge" to distinguish the neutrino states and to define the allowed reactions, l_e , which we require to be additively conserved

$$\sum_{in} l_e = \sum_{out} l_e$$

$lepton$	l_e
e^-	$+1$
e^+	-1
ν_e	$+1$
$\bar{\nu}_e$	-1

Historical footnote:

- connected with the Cl solar neutrino detector: after Pontecorvo's suggestion, Alvarez did a detailed background study for this detector for a potential reactor experiment, but did not pursue a measurement

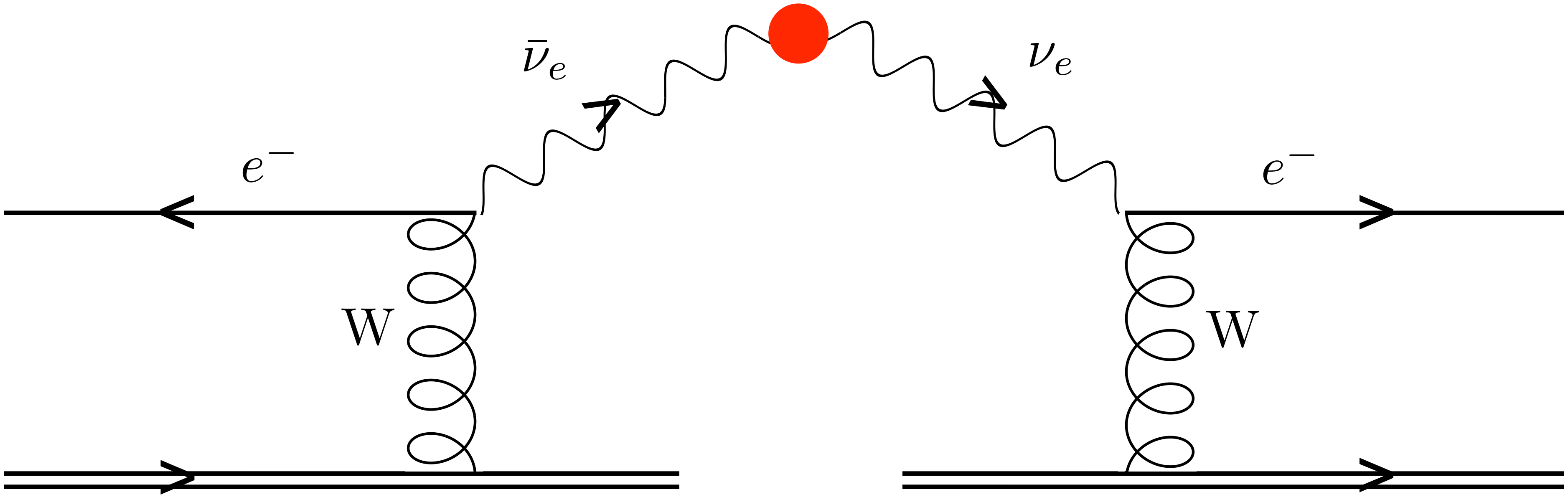
- Davis's BNL program included a Savannah River experiment in which reactor anti-neutrinos

$$^{37}\mathrm{Cl} + \bar{\nu}_e \rightarrow {}^{37}\mathrm{Ar} + e^-$$

failed to produce Ar, indicating that the ν_e and $\bar{\nu}_e$ are distinct at $\sim 5\%$, a prejudice embedded in the standard model

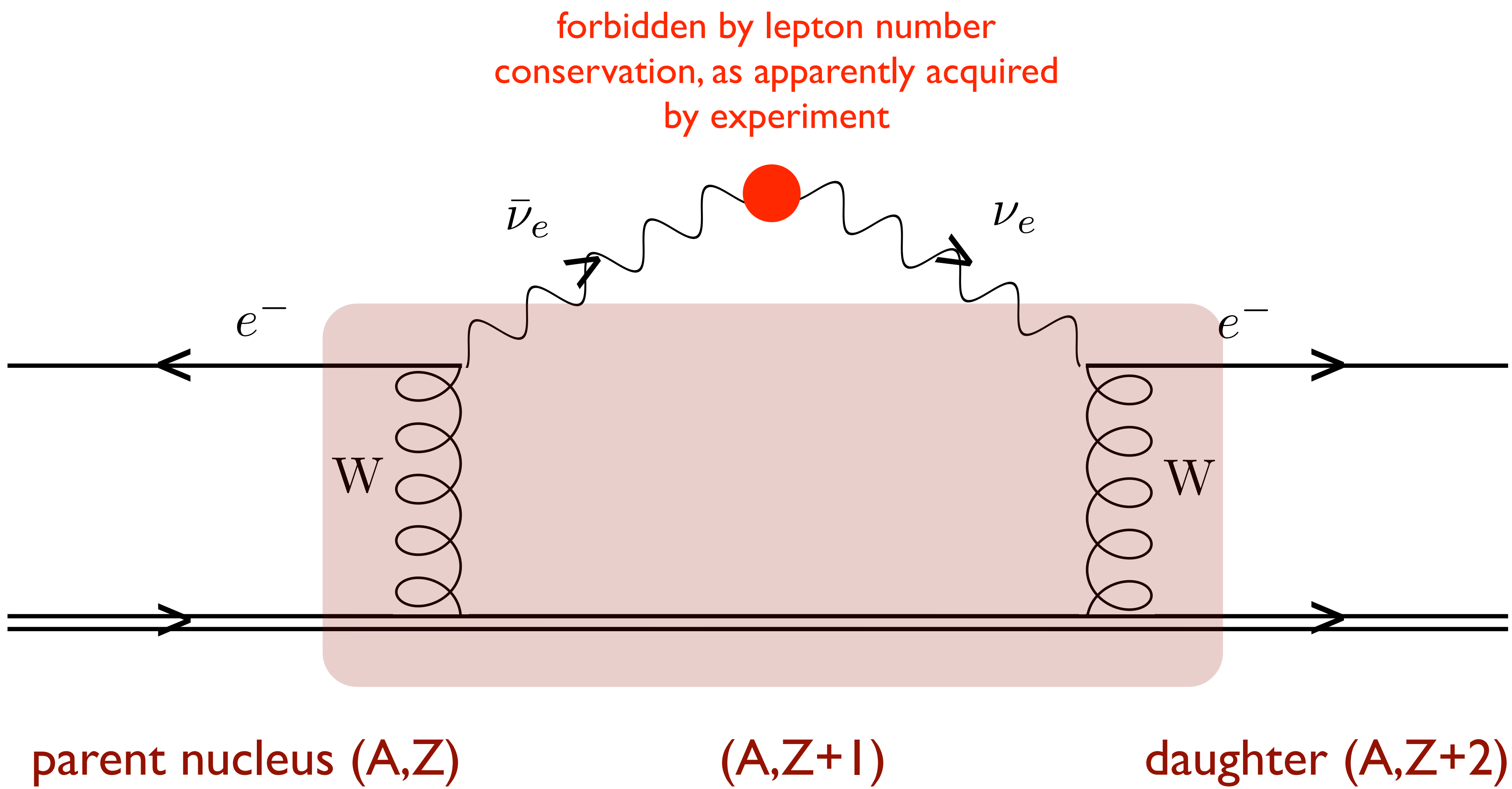
forbidden by lepton number
conservation, as apparently acquired
by experiment

The described experiment



source (A,Z)   (A,Z+1)   target (A',Z')   (A',Z'+1)

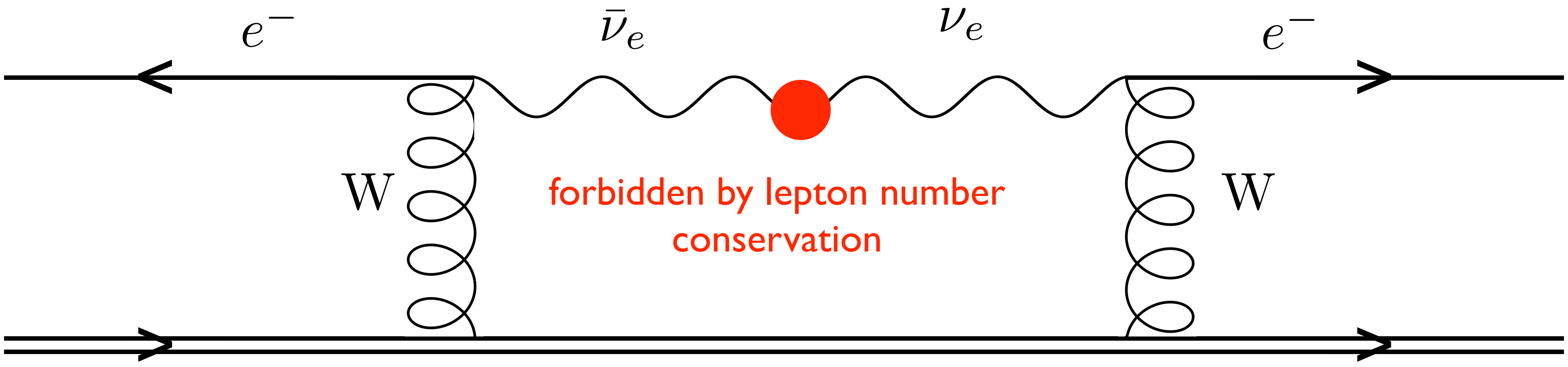
can be done virtually in the process of ββ decay



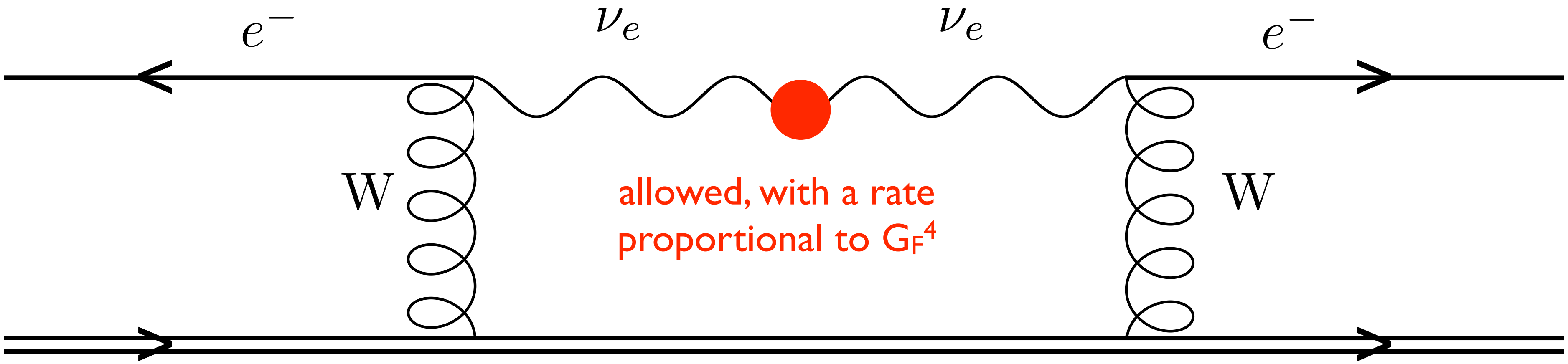
The nucleon pairing interaction gives us ~ 50 nuclear "laboratories" in which to probe symmetry-violating 2nd-order weak interactions

The connection between non-observation of $0\beta\beta \Leftrightarrow$ conserved ν (lepton) charge is altered by ν helicity and consequently by ν mass

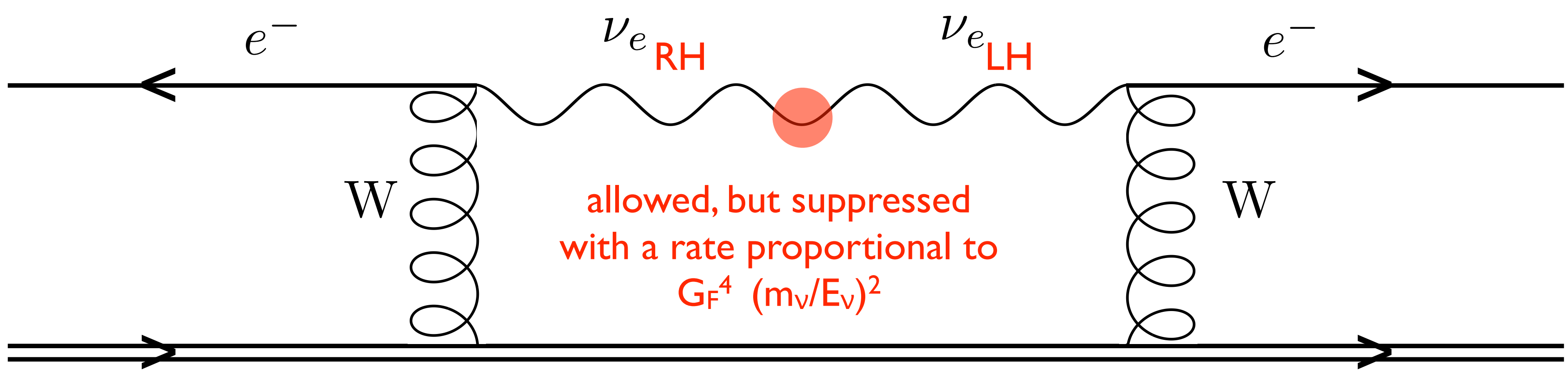
The discovery of apparently maximal PNC in '57 alters the argument:
LHed particles, RHed antiparticles



Remove the restriction of an additively conserved lepton number



and account for suppressed rates by the nearly exact handedness

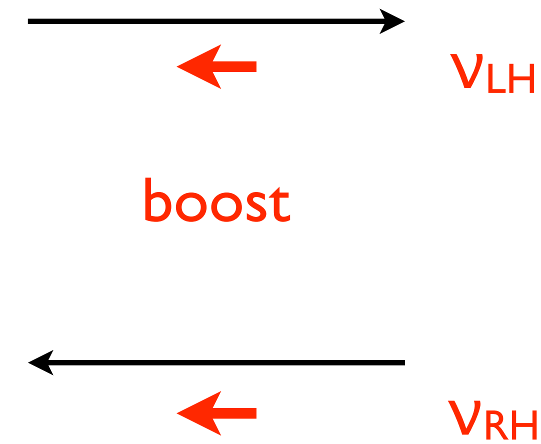


So a Majorana ν, in a theory with exact V-A, is allowed provided the ν mass is sufficiently small that the ν's wrong-helicity component, proportional to m_ν/E_ν, suppresses the ββ rate below experimental bounds

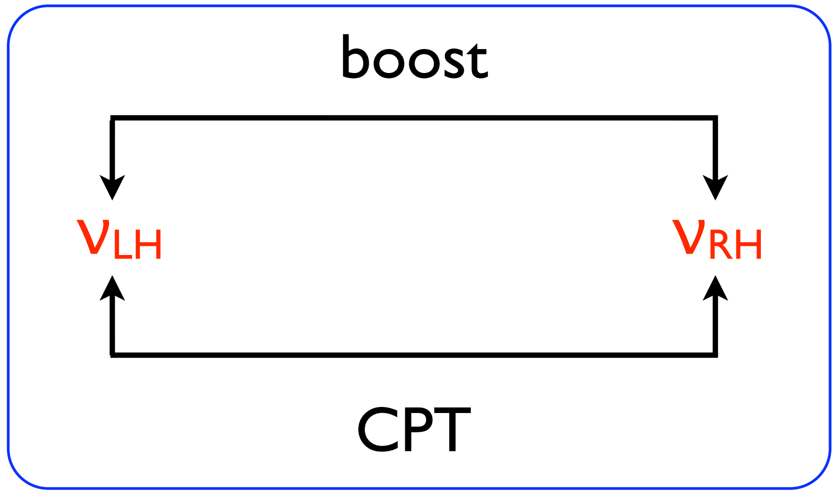
Majorana terms thus perfectly fine. Under the theory that what is not expressly forbidden is then required, νs then allow us to probe a novel mass mechanism that cannot operate for charged SM fermions

Two limiting massive ν descriptions

Lorentz invariance

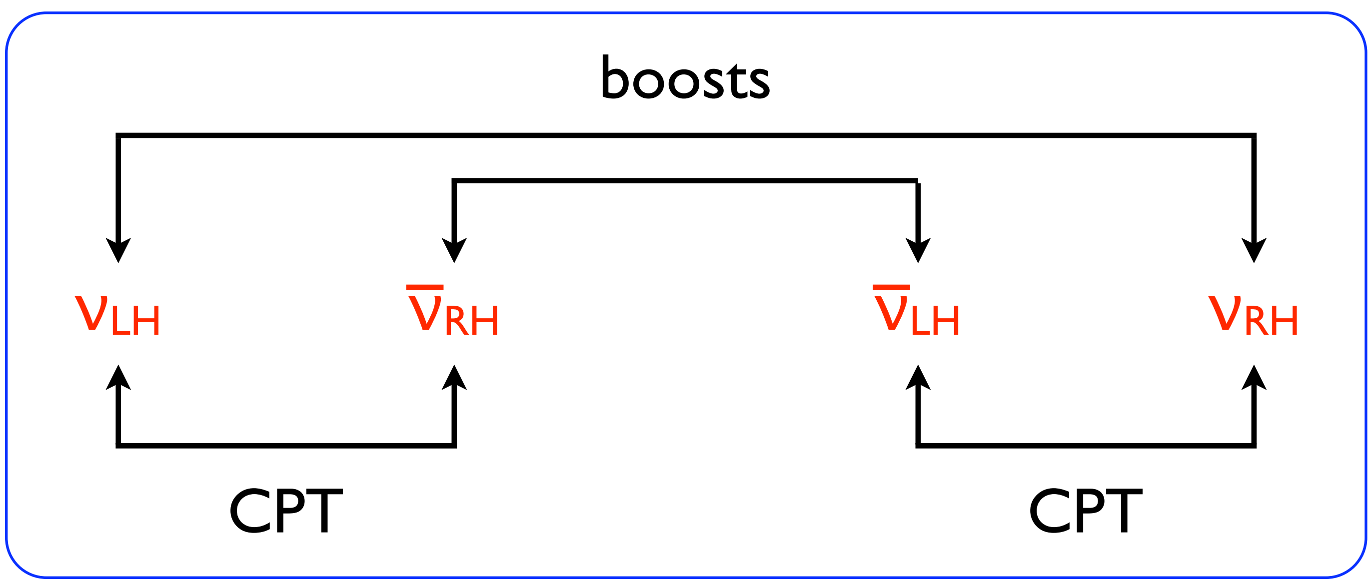


Majorana:



in general, linear combinations of the two

Dirac:



Let's see the mass consequences: start with the Dirac eq., project out

$$\psi_{R/L} = \tfrac{1}{2}(1 \pm \gamma_5)\psi] \qquad\qquad C\ \psi_{R/L}\ C^{-1} = \psi^c_{R/L}$$

Allow for flavor mixing

$$L_m(x) \sim m_D \bar{\psi}(x)\psi(x) \Rightarrow M_D \bar{\Psi}(x)\Psi(x) \qquad\qquad \Psi_L \equiv \begin{pmatrix} \Psi^e_L \\ \Psi^\mu_L \\ \Psi^\tau_L \end{pmatrix}$$

To give the mass 4n by 4n matrix

$$(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R) \begin{pmatrix} 0 & 0 & & M_D^T \\ 0 & 0 & M_D & \\ & M_D^\dagger & 0 & 0 \\ M_D^* & & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

Observe that the handedness allows an additional generalization

$$L_m(x) \Rightarrow M_D \bar{\Psi}(x)\Psi(x) + (\bar{\Psi}^c_L(x) M_L \Psi_L(x) + \bar{\Psi}^c_R(x) M_R \Psi_R(x) + h.c.)$$

to give the more general matrix

$$(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R) \begin{pmatrix} 0 & 0 & M_L & M_D^T \\ 0 & 0 & M_D & M_R^\dagger \\ M_L^\dagger & M_D^\dagger & 0 & 0 \\ M_D^* & M_R & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

which has a number of interesting properties

- the eigenvectors are two-component Majorana spinors: 2n of these
- the introduction of M_L, M_R breaks the global invariance $\Psi \to e^{i\alpha}\Psi$ associated with a conserved lepton number

- the removal of M_L, M_R makes the eigenvalues pairwise degenerate: two two-component spinors of opposite CP can be patched together to form one four-component Dirac spinor -- so one gets n of these

- the mass that appears in double beta decay is $\sum_{i=1}^{2n} U_{ei}^2 \lambda_i m_i$, where λ_i is the ith's neutrino CP eigenvalue and U_{ei}^2 the coupling probability to the electron: this vanishes when $M_L, M_R \to 0$

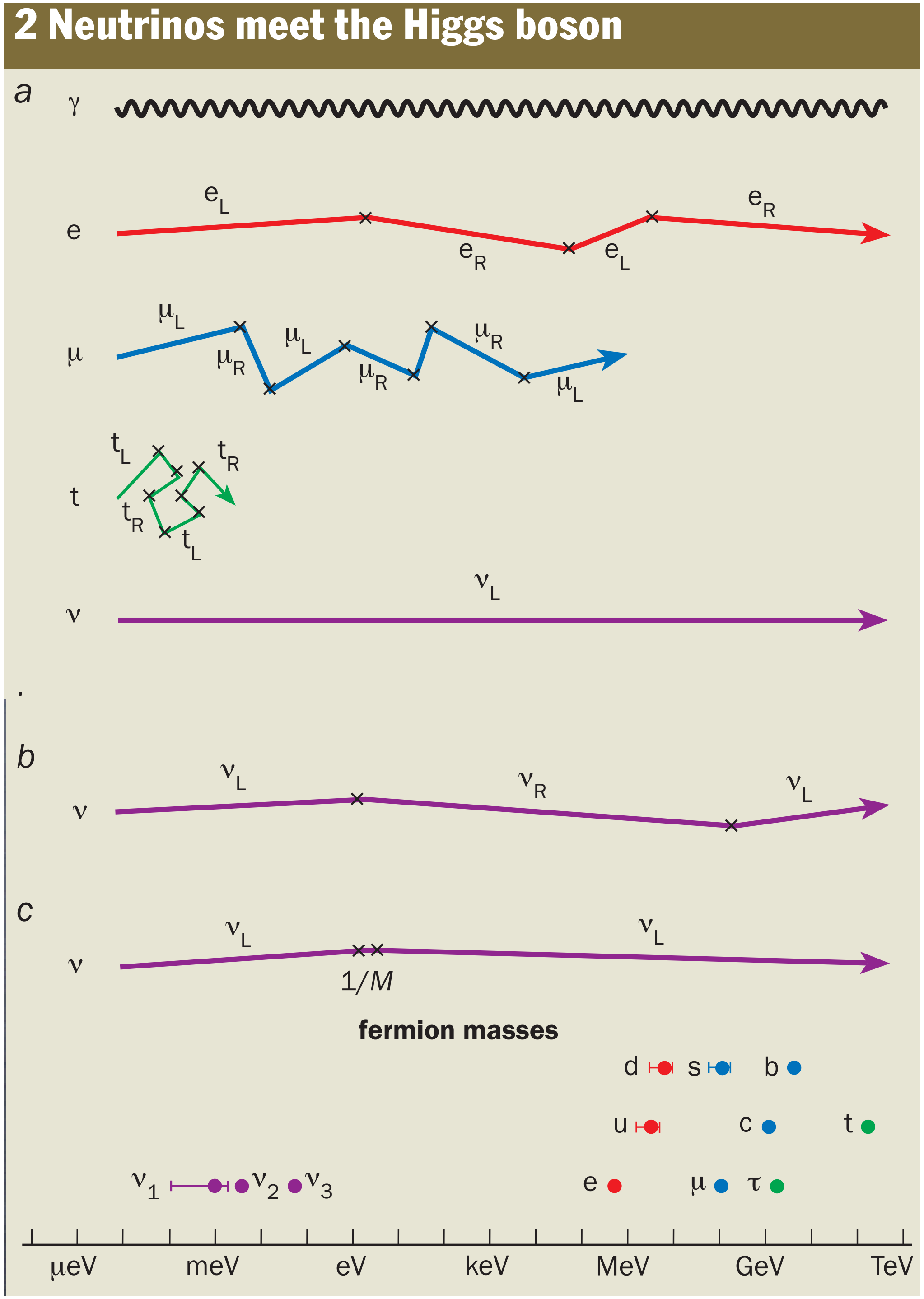
- the MSM has no RHed neutrino field; M_L can be constructed, but does not appear in the MSM because it is not renormalizable

$$M_L \sim \frac{\langle \phi \rangle^2}{M_{new}}$$

  it is the only such dimension-five operator in the SM, and thus a likely source of the new physics that would show the MSM is breaking down

- ββ decay constrains the LHed Majorana mass to be below about an eV

Hitoshi Muryama's ν mass cartoon



standard model masses

light Dirac neutrino

LHed Majorana neutrino

← the anomalous ν mass scale

The ν's more general mass ⇒ explanation ν mass scale

- give the ν an M_D typical of other SM fermions

- take $M_L \sim 0$, in accord with $\beta\beta$ decay

- assume $M_R >> M_D$ as we have not found new RHed physics at low E

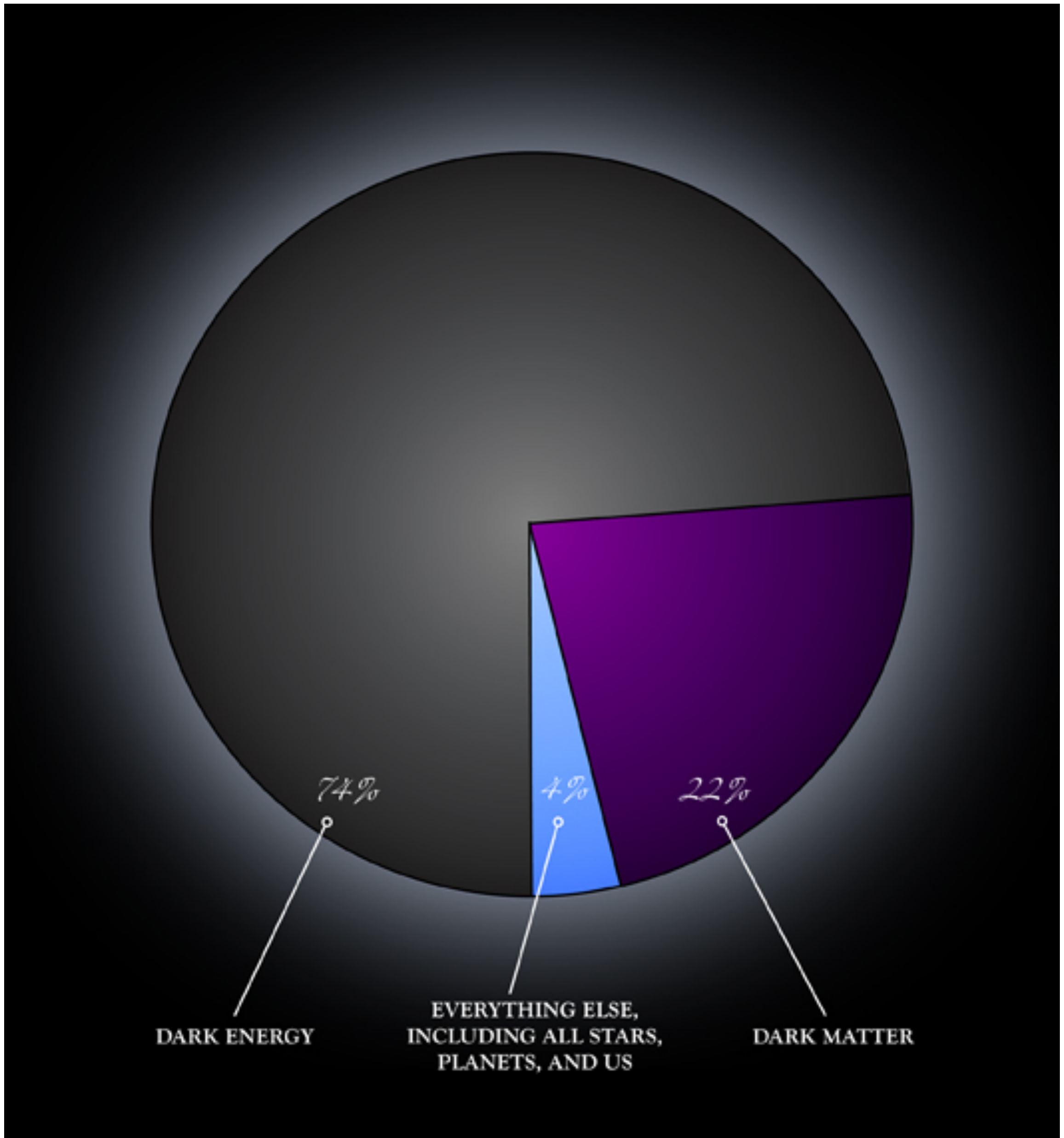
$$\begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \Rightarrow \; m_\nu^{\text{light}} \sim m_D \left(\frac{m_D}{m_R} \right)$$

- take $m_\nu \sim \sqrt{m^2{}_{23}} \sim 0.05$ eV and $m_D \sim m_{top} \sim 180$ GeV

$$\Rightarrow m_R \sim 0.3 \times 10^{15} \text{ GeV}$$

So this was the source of the excitement with the SK and SNO discoveries of 1998-2002: *the deduced ν mass differences are consistent with a novel mass generation mechanism, not shared by other SM fermions, that the data suggest might be characteristic of the GUT scale*

II. The inner space ⇔ outer space connection: exotic astro environments testing νs ⇒ lab

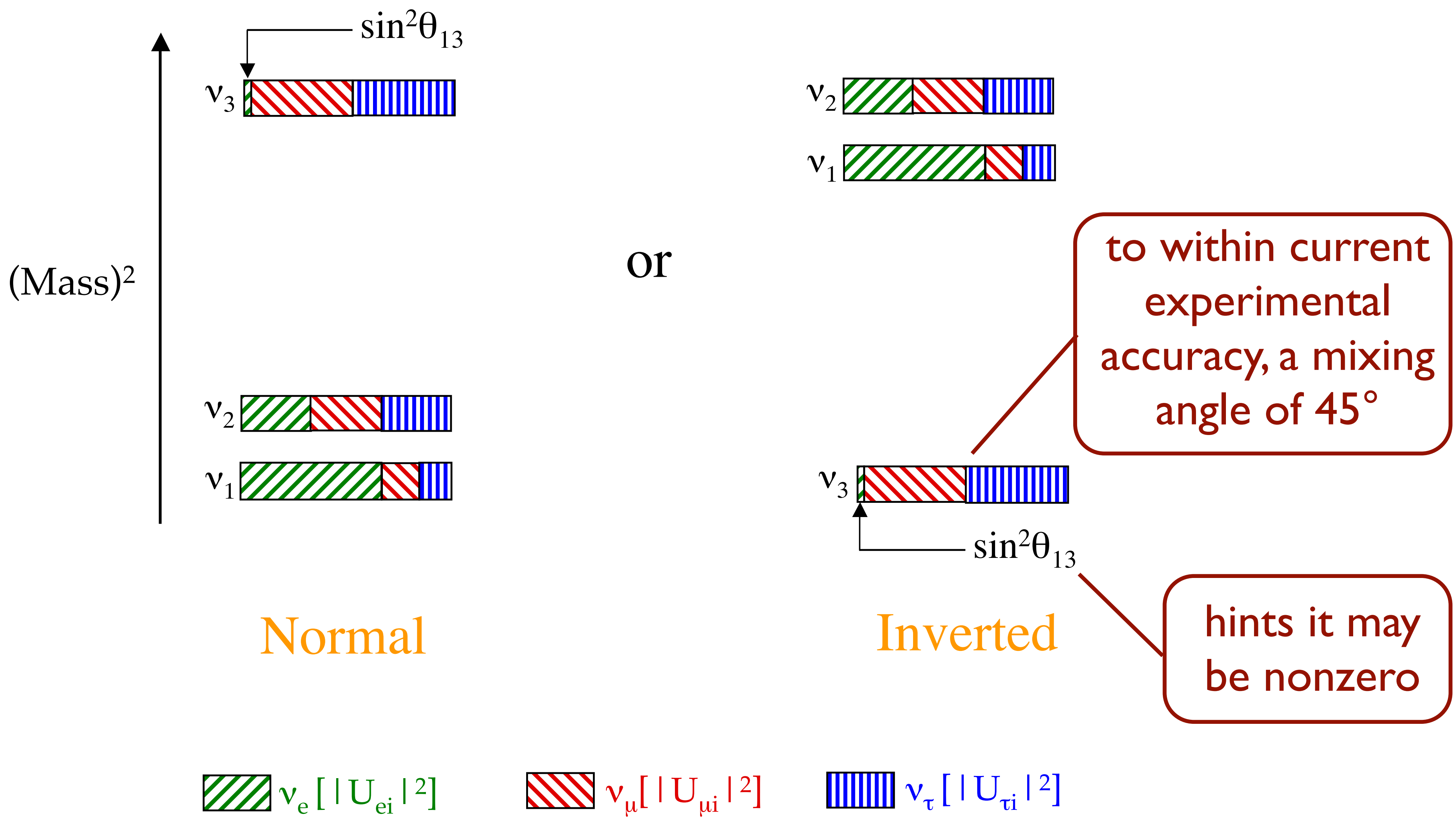


Deep issues regarding mass seem connected to the large-scale properties of our universe: νs involved

- baryon asymmetry
- net mass in SM particles
  - from BBN directly
  - from baryon-DM interactions @ 400K y
- DM density
- the bounds on the ν contribution to DM
- ν mass differences
- the curious conspiracy of DM and DE that yields $\Omega=1$ and DM ~ DE today

Our initial results on neutrino properties

Hierarchy



(artwork: Boris Kayser)

The mixing (where we have additional blanks to fill in)

knowns: θ_{12}, θ_{23} known unknowns: θ_{13} δ, ϕ_1, ϕ_2

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ e^{i\phi_1}\nu_2 \\ e^{i\phi_2}\nu_3 \end{pmatrix}$$

$$= \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & \boxed{s_{13}}e^{\boxed{-i\delta}} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \boxed{e^{i\phi_1}}\nu_2 \\ \boxed{e^{i\phi_2}}\nu_3 \end{pmatrix}$$

atmospheric ν_e disappearance solar

results: $\theta_{23} \sim 45^\circ$ $\sin\theta_{13} \leq 0.17$ $\theta_{12} \sim 30^\circ$

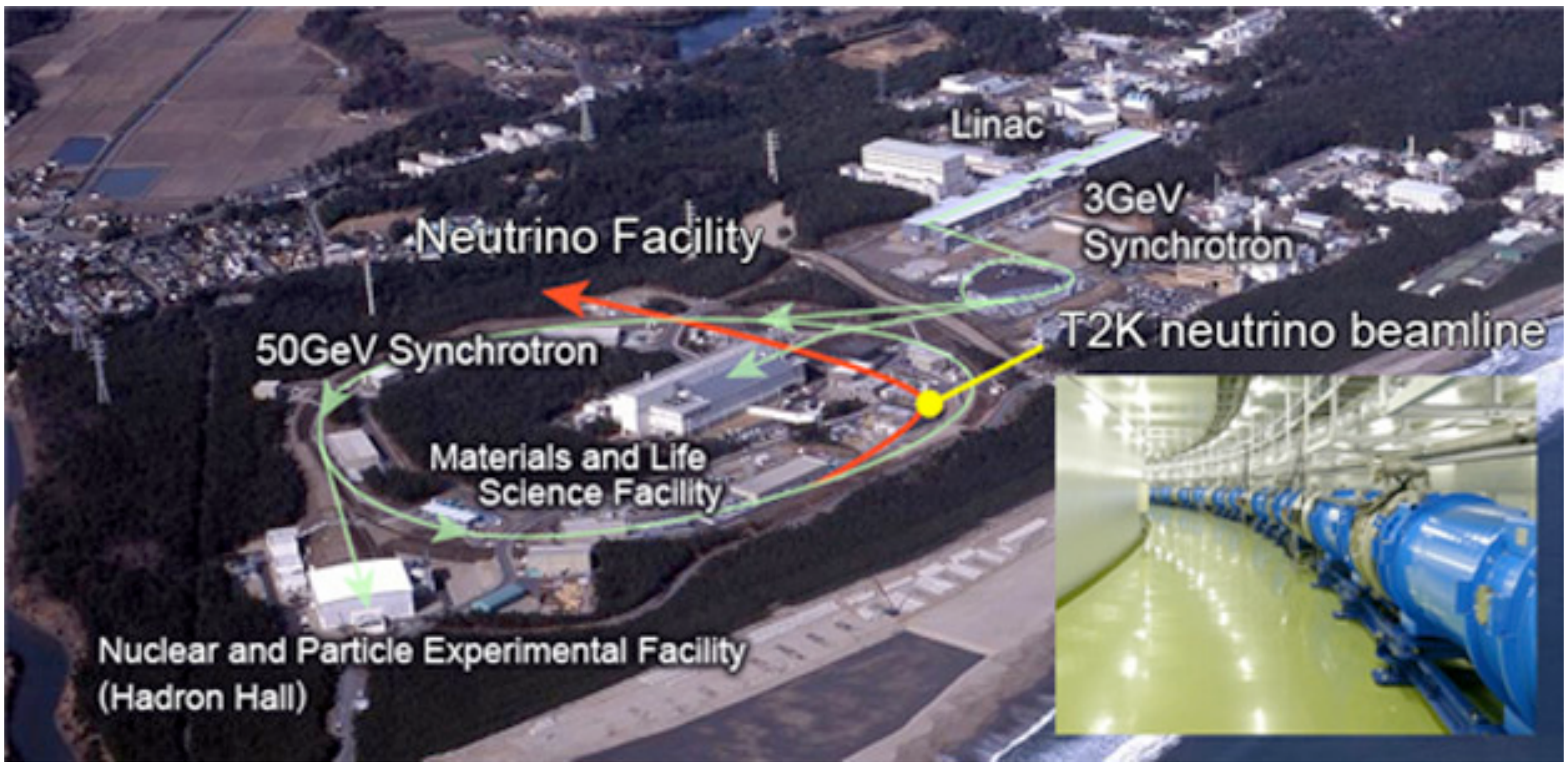
Δ_{12} $|\Delta_{23}|$ $\boxed{\mathrm{sign}[\Delta_{23}]}$ $\boxed{\text{absolute scale}}$

Astrophysics has inventoried SM mass @ 4%: B asymmetry requirements:

- baryon number violation
- out of equilibrium interactions
- C and CP violation: known SM $\cancel{C}$P sources appear insufficient

but $$J^{\nu}_{CP} = \sin\theta_{12}\sin\theta_{23}\sin\theta_{13}\cos\theta_{12}\cos\theta_{23}\cos\theta_{13}{}^2\sin\delta$$
$$\sim 0.2\sin\theta_{13}\sin\delta$$

T2K $\nu_\mu \to \nu_e$ search



Experimental parameters

- 2.5° off-axis relatively narrow ν beam, yielding $E_\nu^{\rm peak} \sim$ 0.6 GeV

- the J-PARC : SuperK baseline, which then places the detector at the Δm_{23} first oscillation maximum

- $\nu_\mu \rightarrow \nu_e$ appearance at a baseline much shorter than that optimizing appearance via θ_{12}, so the effects of θ_{13} can be seen

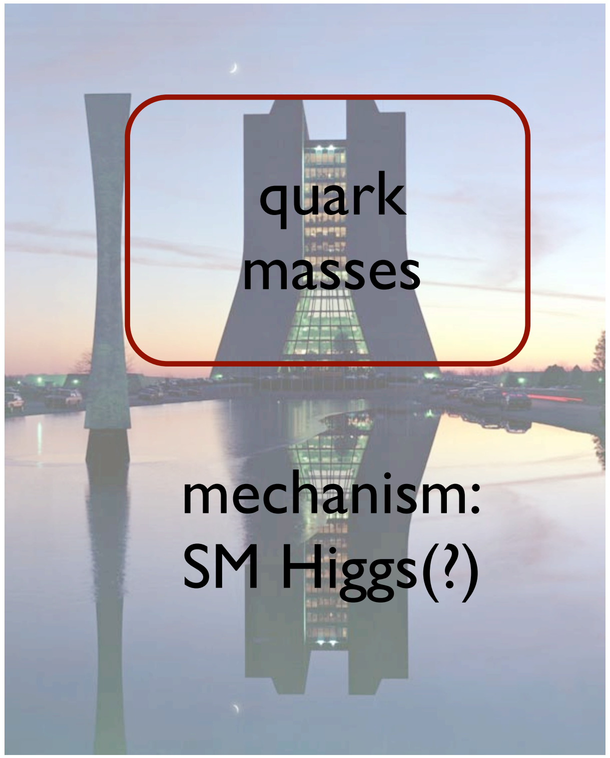
find 6 events when 1.5 ± 0.3 would be expected were θ_{12} = 0 (2.5 σ)

deduce $0.03(0.04) \lesssim \sin^2 2\theta_{13} \lesssim 0.28(0.34)$ normal(inverted), δ_{CP} = 0

compares to CHOOZ, MINOS $\sin^2 2\theta_{13} \lesssim 0.15$ and potentially indicates significant future LBNE sensitivity to δ_{CP} = 0

So it is quite possible that νs determined the SM mass inventory
And one hopes low-E $\cancel{C}$P parameters ⇒ high-T leptogenesis

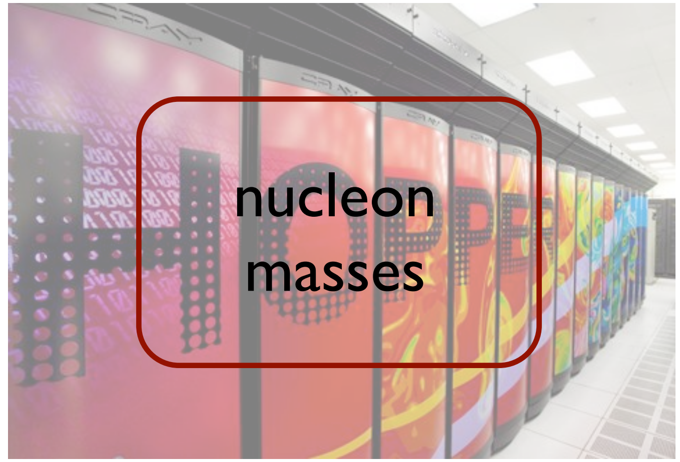
Baryonic mass at low T: Once $\eta = n_B/n_\gamma$ is set, the evolution to the end state of H and He is both interesting and ν driven



quark masses	→	nucleon masses	nuclear masses
mechanism: SM Higgs(?)		99% of baryonic mass is glue	almost none of the mass in interaction

this "condensed matter" problem may seem pedestrian, but it actually quite curious

H and He: νs at high early-universe temperatures may determine $\eta = n_B/n_\gamma$. There is a curious mapping of that mass onto our low-T world



quark masses

nucleon masses

→

nuclear masses

mechanism: SM Higgs

99% of baryonic mass is glue

almost none of the mass in interaction

FermiQCD

A toolkit for fast development of parallel Lattice QCD applications

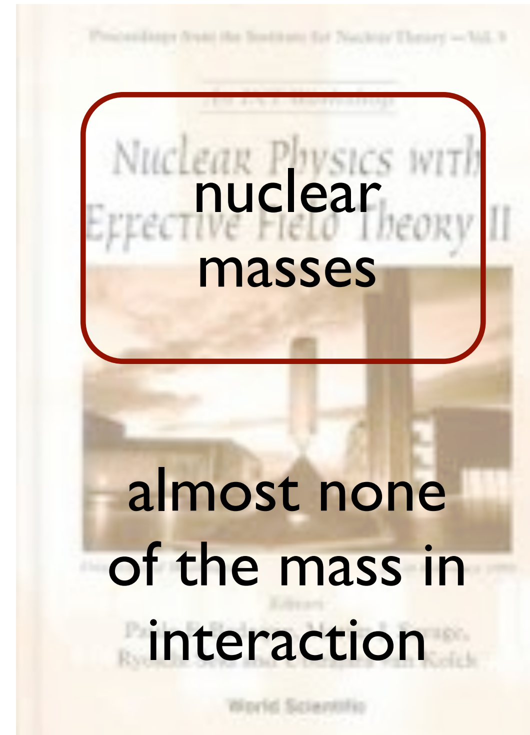
<u>Baryonic mass</u>: νs at high early-universe temperatures may determine $\eta = n_B/n_\gamma$. There is a curious mapping of that mass onto our low-T world

quark masses

mechanism: SM Higgs

nucleon masses

99% of baryonic mass is glue



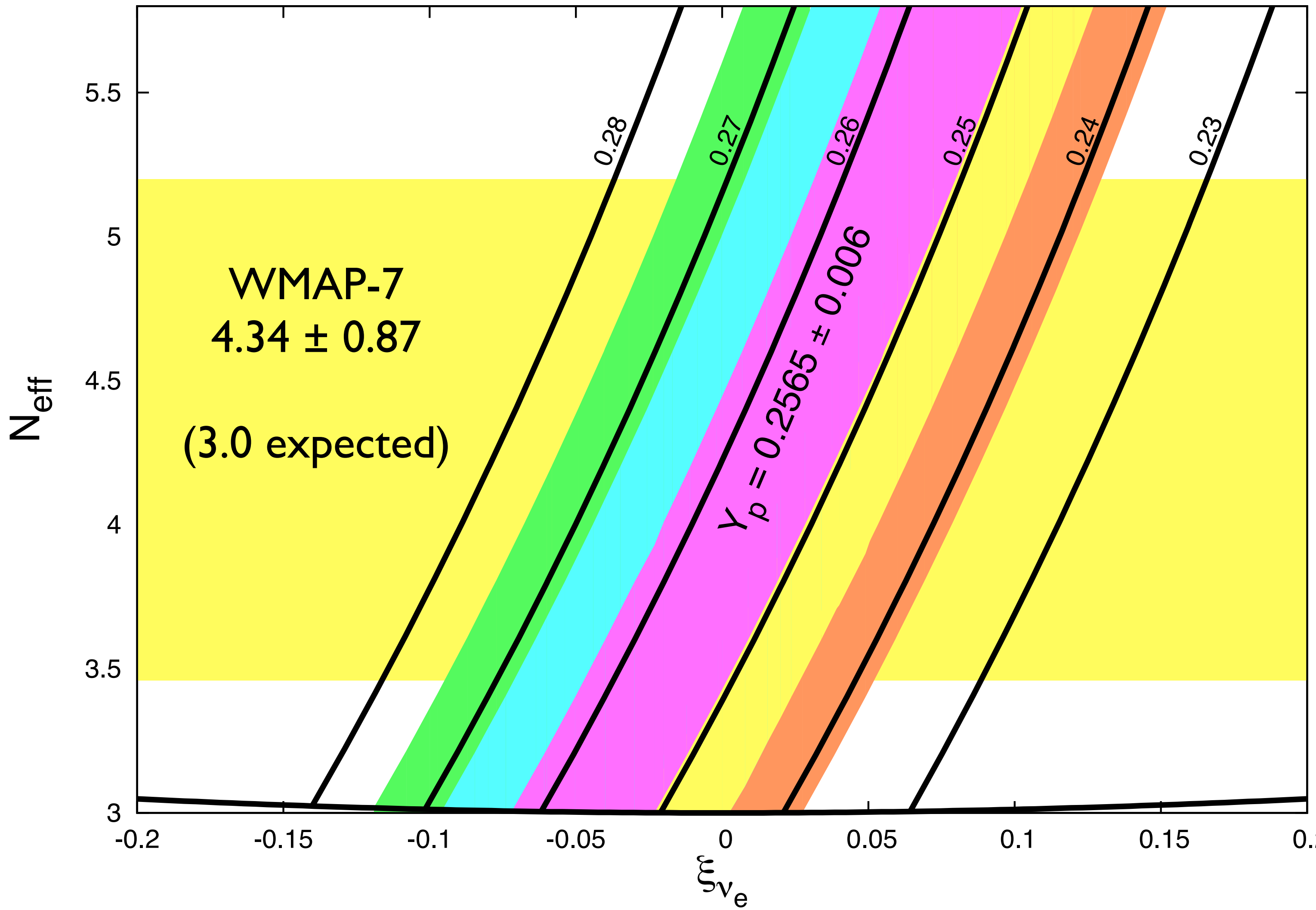
nuclear masses

almost none of the mass in interaction

BBN production of H/He used to be our way of measuring net SM mass. but WMAP determined $\eta = n_B/n_\gamma$ fixing the one free BBN parameter $\Rightarrow$

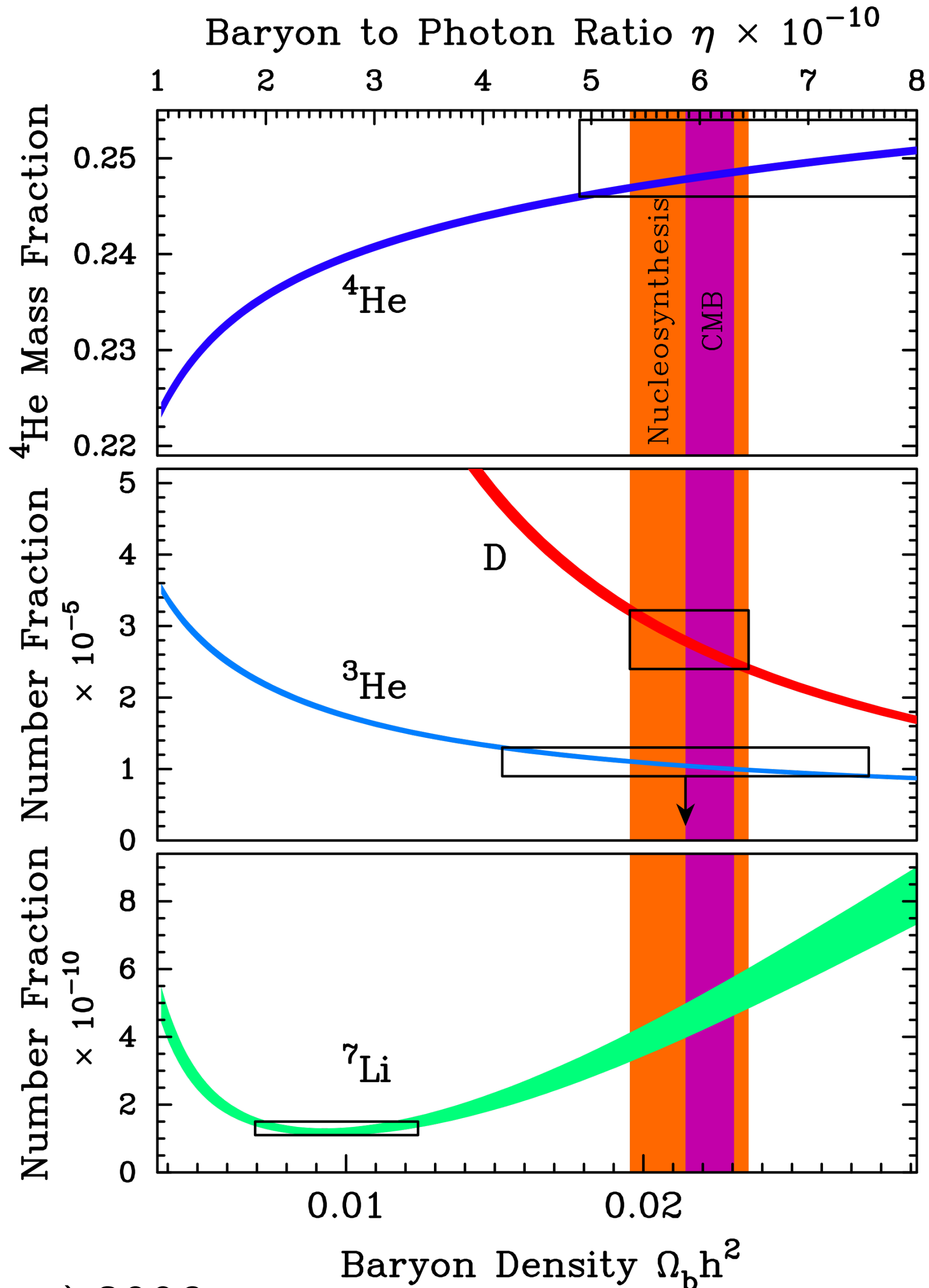
now largely a test of the ν physics of the early universe

Competing clocks of expansion driven by the relativistic species and weak interactions driving n densities downward



Krauss, Lunardini, Smith

BBN and CMB studies constrain the ν number and asymmetry
weak hints that all is not right (but best to wait for Planck...)



also, a puzzle with ^{7}Li, which has a well-defined primordial abundance plateau, but not one consistent with BBN and known uncertainties

Nao Suzuki (Tytler group) 2006

Absolute ν mass scale: the one "known" component of DM is the ν

To "measure" ν mass cosmologically at $\sqrt{\Delta m_\nu^{2\ \mathrm{atmos}}}$, need a sensitivity to hot dark matter at ~ .001 ρ_{crit} : current sensitivity ~ .013 ρ_{crit}

νs with a smaller mass remain relativistic longer, travel further, and suppress growth of structure on larger scales

Thus ν influences on structure *evolve* with both redshift Z and spatial scale in a characteristic way:

$$k_{\mathrm{free\ streaming}} \sim 0.004\sqrt{m_\nu/0.05\mathrm{eV}}\ \mathrm{Mpc}^{-1}$$

$$\sum m_\nu \sim 0.05\ \mathrm{eV},\ \ z = \begin{pmatrix} 3.5 \\ 3.5 \\ 1.5 \\ 0.0 \end{pmatrix} \Rightarrow \text{ power decrease} \sim \begin{pmatrix} 1.9\% \\ 1.0\% \\ 2.1\% \\ 3.5\% \end{pmatrix} \text{ for } k > \begin{pmatrix} 0.6 \\ 0.03 \\ 0.6 \\ 0.6 \end{pmatrix} \frac{1}{\mathrm{Mpc}}$$

νs alter the evolution of the the baryons + CDM at the few % level, though they comprise only 0.1% of today's energy density the precision of LSS surveys scales $\propto 1/\sqrt{N}$, so a factor of 100 needed

effects that are scale-dependent at fixed Z, and evolve in a characteristic way with Z, can be differentiated from other parameter changes

there are a variety of both high-Z and low-Z surveys in preparation that envision such enlarged data sets

- various analyses of combined projected data sets (high-redshift galaxy surveys, SDSS-III BOSS 10^5 QSO survey, Planck CMB data, 21cm radio telescopes with 0.1 km^2 collection, weak lensing ...) sensitive to $m_\nu \sim 50$ meV at $1-7\sigma$

combine data sets to span the greatest possible range of Z and scale

could get lucky and determine the hierarchy (< 100 meV)

systematics could dominate: will the various data sets that sampling Z and scale yield a consistent picture when combined?

Mass differences, oscillations: Vacuum oscillations for an extended source

$$1 - \frac{1}{2}\sin^2 2\theta_{12}$$

But νs acquire an effective mass in matter, with distinctive effects arising when: the effective mass ~ the vacuum mass difference

$$\rho_{\rm res} \sim 1.3 \times 10^6 \left(\frac{\Delta m^2}{\rm eV^2}\right)\left(\frac{5\ \rm MeV}{E_\nu}\right)\left(\frac{0.5}{Y_e}\right)\cos 2\theta\ \ {\rm g/cm^3}$$

The great good fortune in solar νs comes from Nature's choice

$$\delta m^2_{12} \sim 8 \times 10^{-5} {\rm eV}^2$$

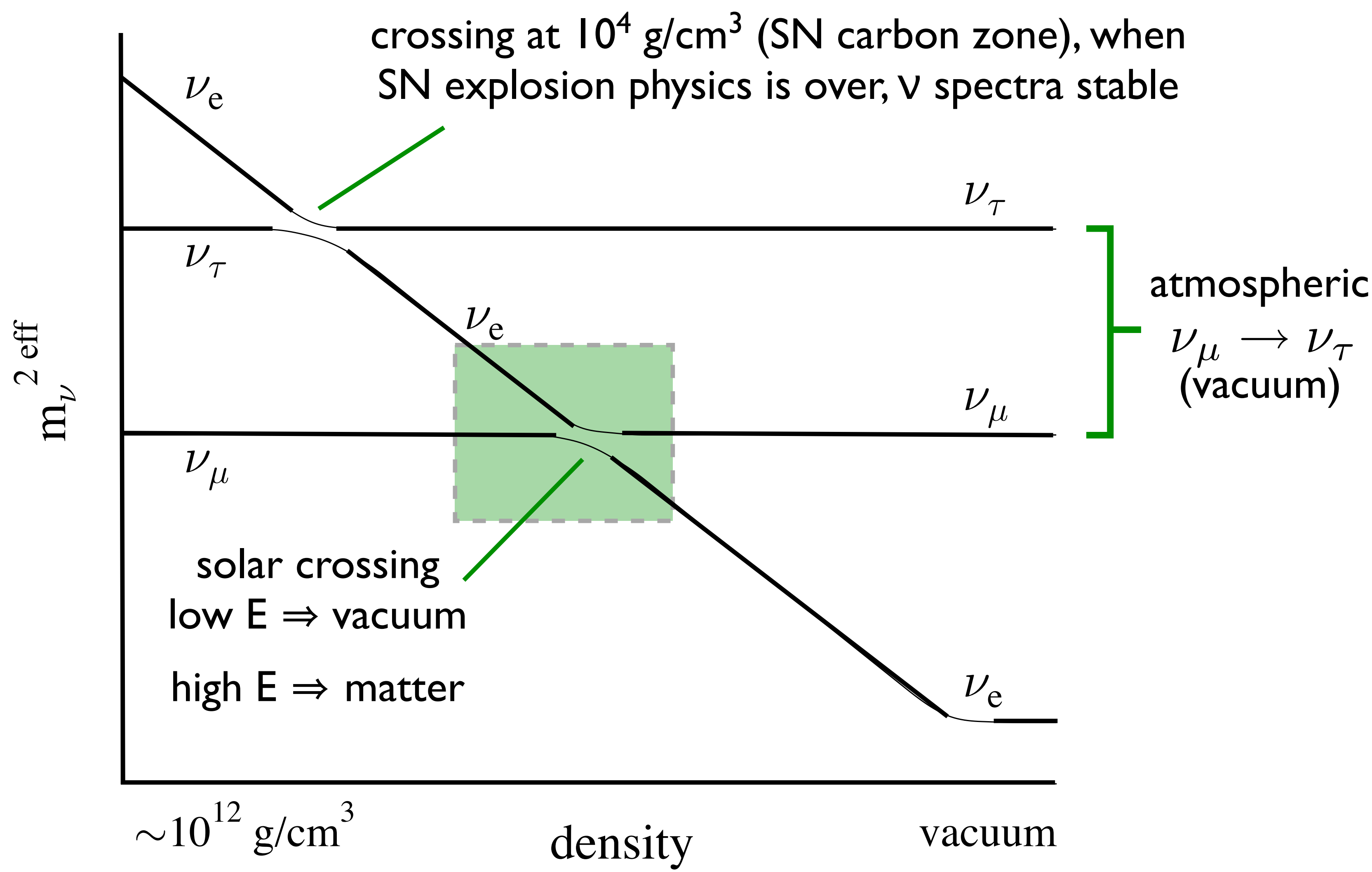
so that $\rho_{\rm res}(E_\nu \sim 10\ \rm MeV) \sim 25\ g/cm^3 < \rho_{\rm core}$

$$\rho_{\rm res}(E_\nu \sim 1\ \rm MeV) \sim 250\ g/cm^3 > \rho_{\rm core}$$

By observing the matter effects on ν_e , one extracts the sign of Δm_{12}

But Δ_{13} ?

matter effects will alter the fluxes from the next galactic supernova



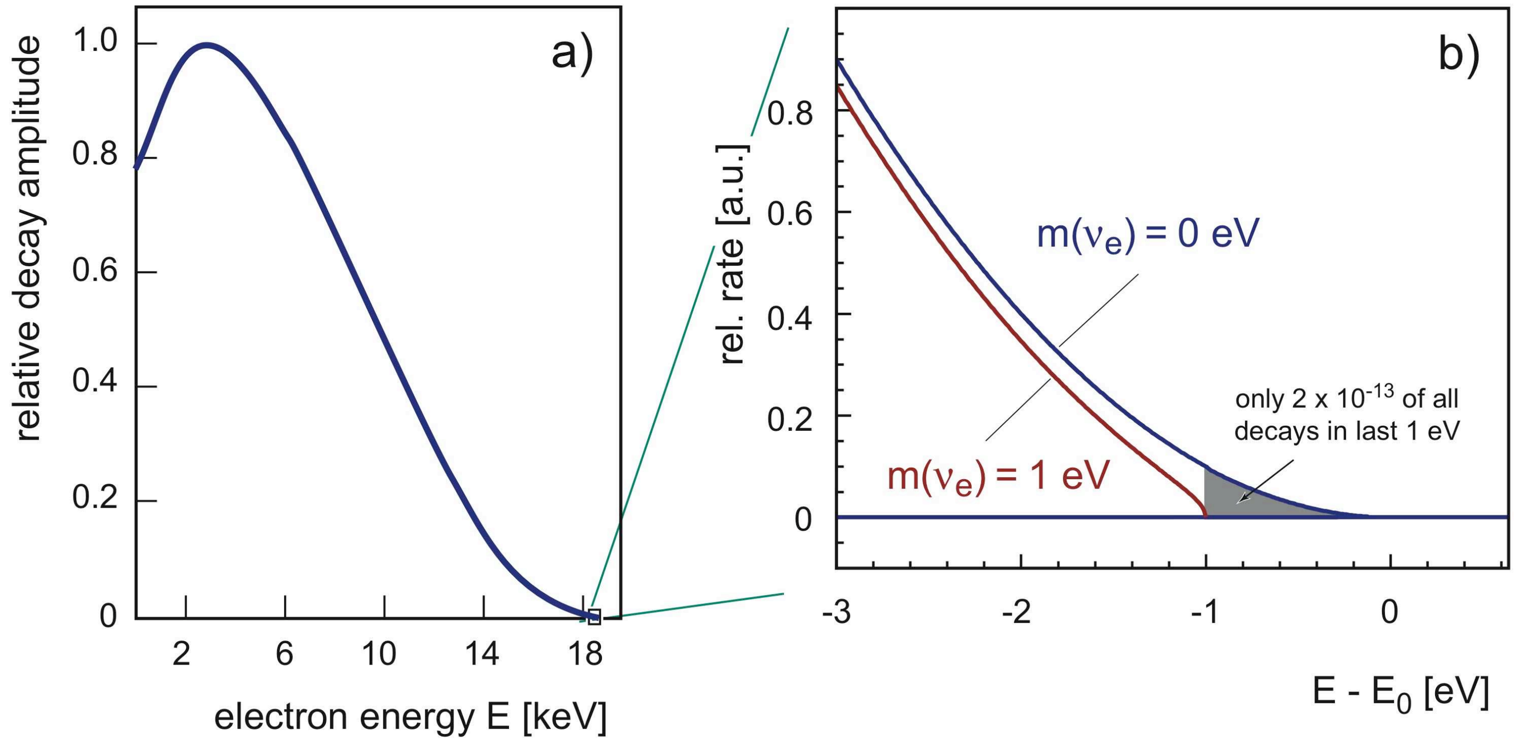
If the T2K results hold up, the MSW mechanism will alter SN physics: the transition is adiabatic unless θ_{13} is very small, < 10^{-4}

III. Lab experiments: we need to get on with it

If there are no surprises, progress is still needed in four areas

1) absolute mass scale
2) lepton number and the mass mechanism
3) the hierarchy and related issues of 1-3 matter effects
4) CP violation

Absolute ν mass: the one identified component of DM



tritium β decay is running into intrinsic limits due to feasible source intensities and detector resolution

$$\langle m_\nu \rangle_{\mathrm{tritium}} = \sum_i |U_{ei}|^2 m_\nu^2(i)$$

present limit $\langle m_\nu \rangle_{\rm tritium} < 2.2 \text{ eV}$ Mainz & Troitzk

KATRIN's goal is to reach 250 meV, with 5σ exclusion at 350 meV

the measurement is clean, and one could get lucky ... but cosmology may provide our best hope of reaching the 50 meV level lepton number and the mass mechanism: neutrinoless ββ decay

$$\langle m_\nu^{\rm Maj} \rangle = \sum_{i=1}^{2n} \lambda_i U_{ei}^2 m_i \quad \text{or} \quad \langle \frac{1}{m_\nu^{\rm heavy}} \rangle = U_{ei}^2 \frac{1}{m_i^{\rm heavy}}$$

analogous to the search for the Higgs

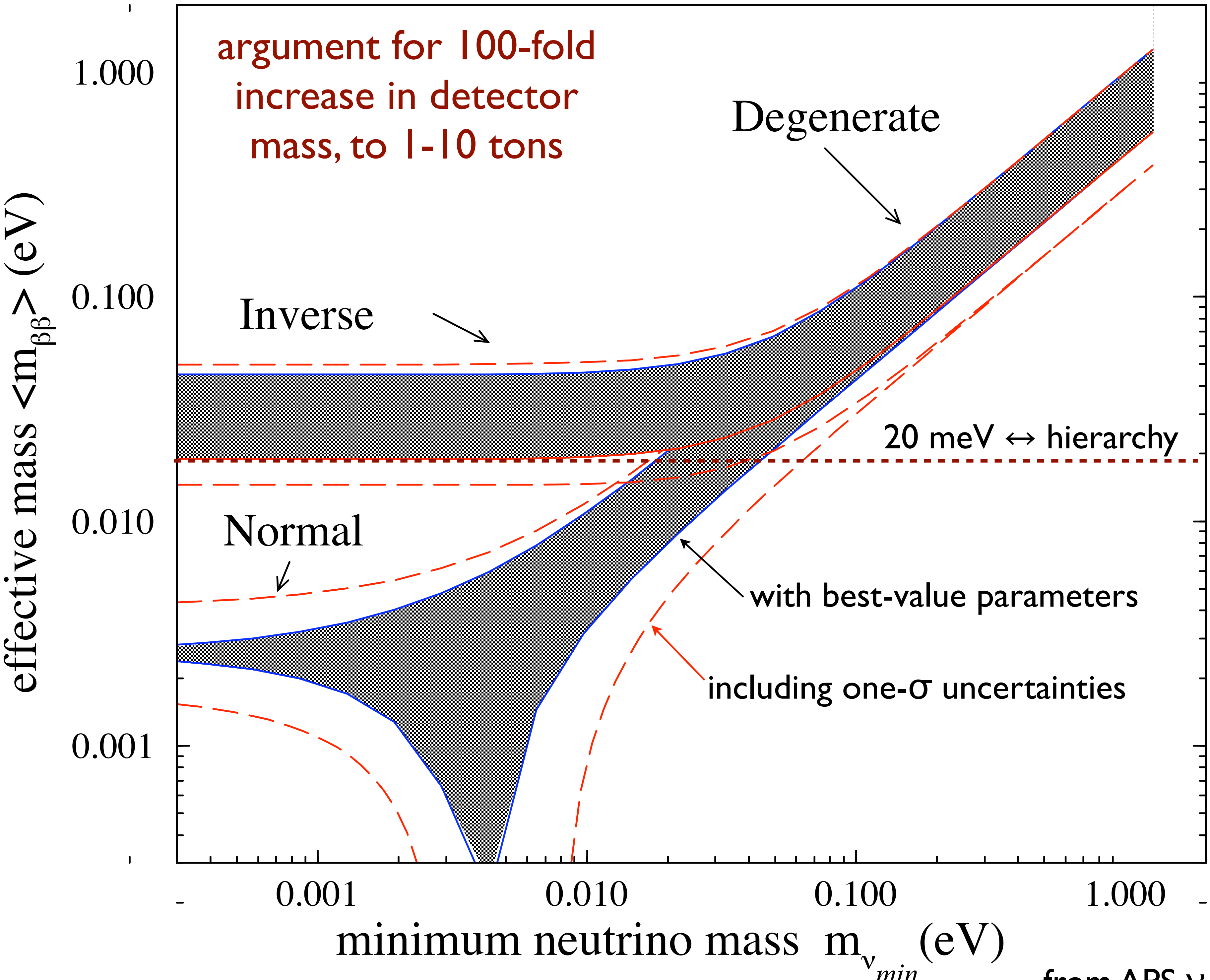
- a mass mechanism connected to the simplest effective SM operator
- indirect sensitivity to near-GUT-scale physics
- direct sensitivity to heavy-ν super-TeV physics

GERDA (^{76}Ge), CUORE (^{128}Te) currently limit

$$\langle m_\nu^{\rm Maj} \rangle < (0.3 - 1.0)\ \text{eV} \qquad \langle \frac{1}{m^{\rm heavy}} \rangle < \frac{1}{10^4\ \text{TeV}}$$

puzzles me why this problem is not being attacked with more urgency and at a more elevated scale:

the physics is unique, the potential implications profound, the discovery potential quite high



from APS ν Study

The hierarchy:

This may be the (known) ν-physics issue of most significance to astro

- it affects the interpretation of the mass sum that will emerge from the next decade of cosmological LLS measurements

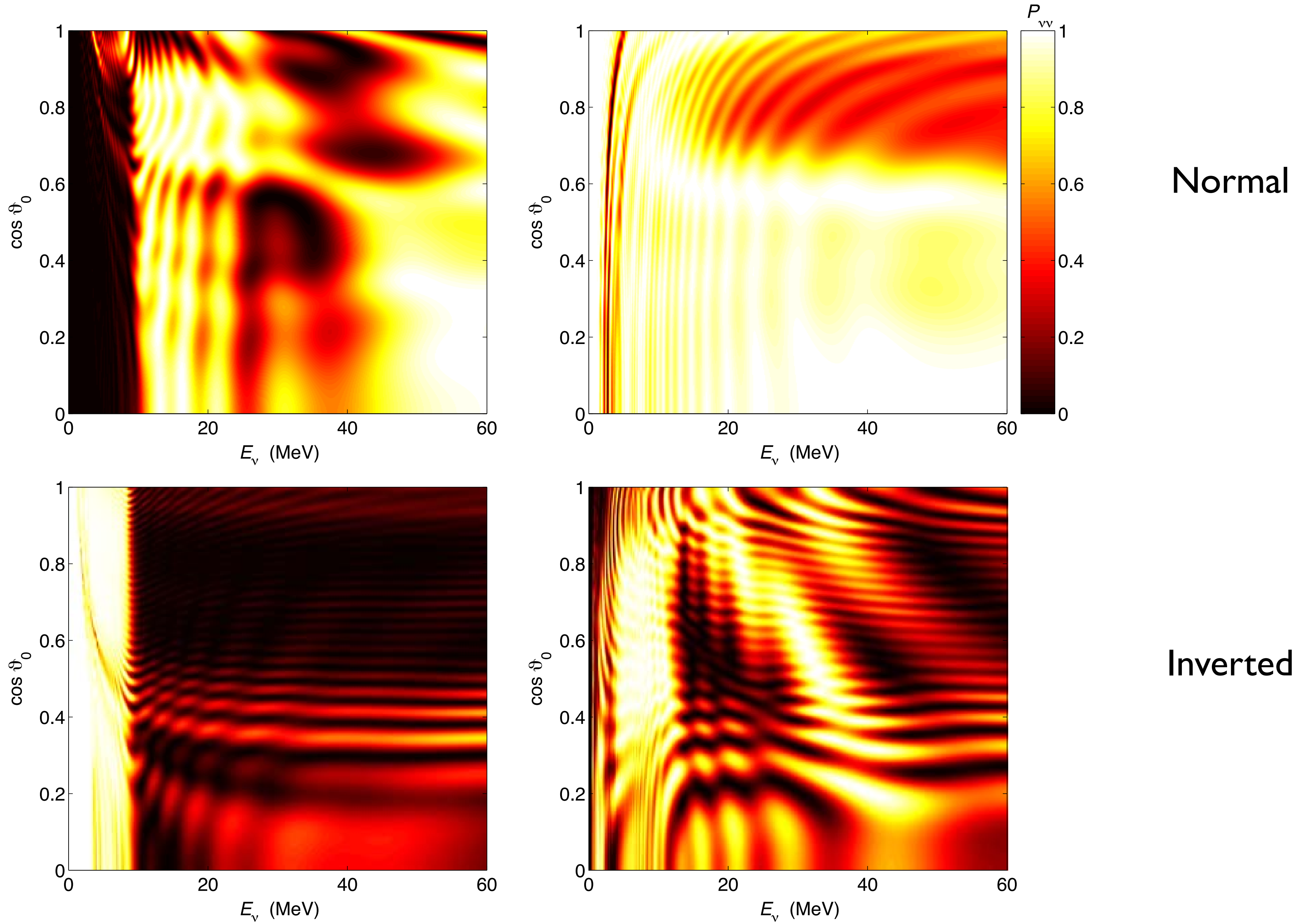
- it alters the flavors of supernova νs, where in the absence of oscillations

$$T_{\text{heavy flavor}} > T_{\bar{\nu}_e} > T_{\nu_e}$$

  consequently affecting energy deposition, nucleosynthesis, and the interpretation of signals seen in terrestrial detectors

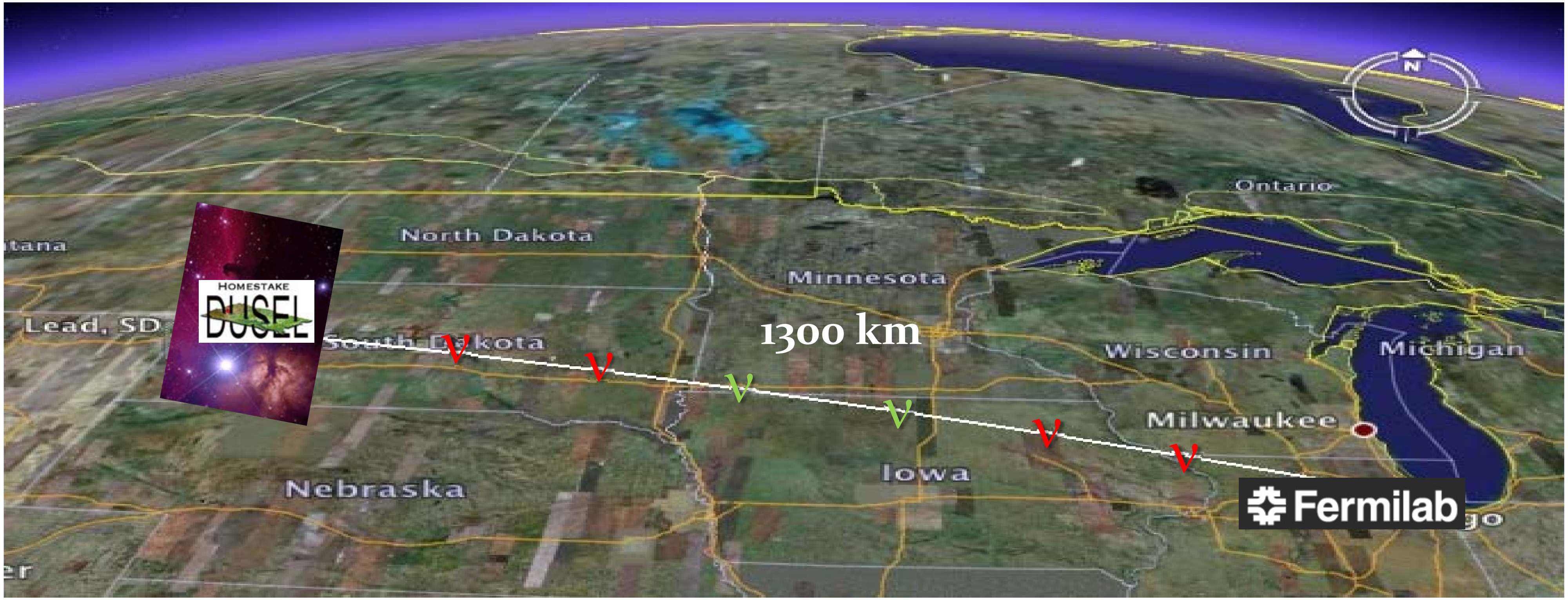
- it qualitatively alters a new ν phenomenon we can only study in supernovae, a nonlinear MSW mechanism arising from ν-ν_{trapped} interactions that is hypersensitive to hierarchy

From Duan et al.



r ~ 225 km! deep in the supernova core

LBNE: hierarchy and CP violation

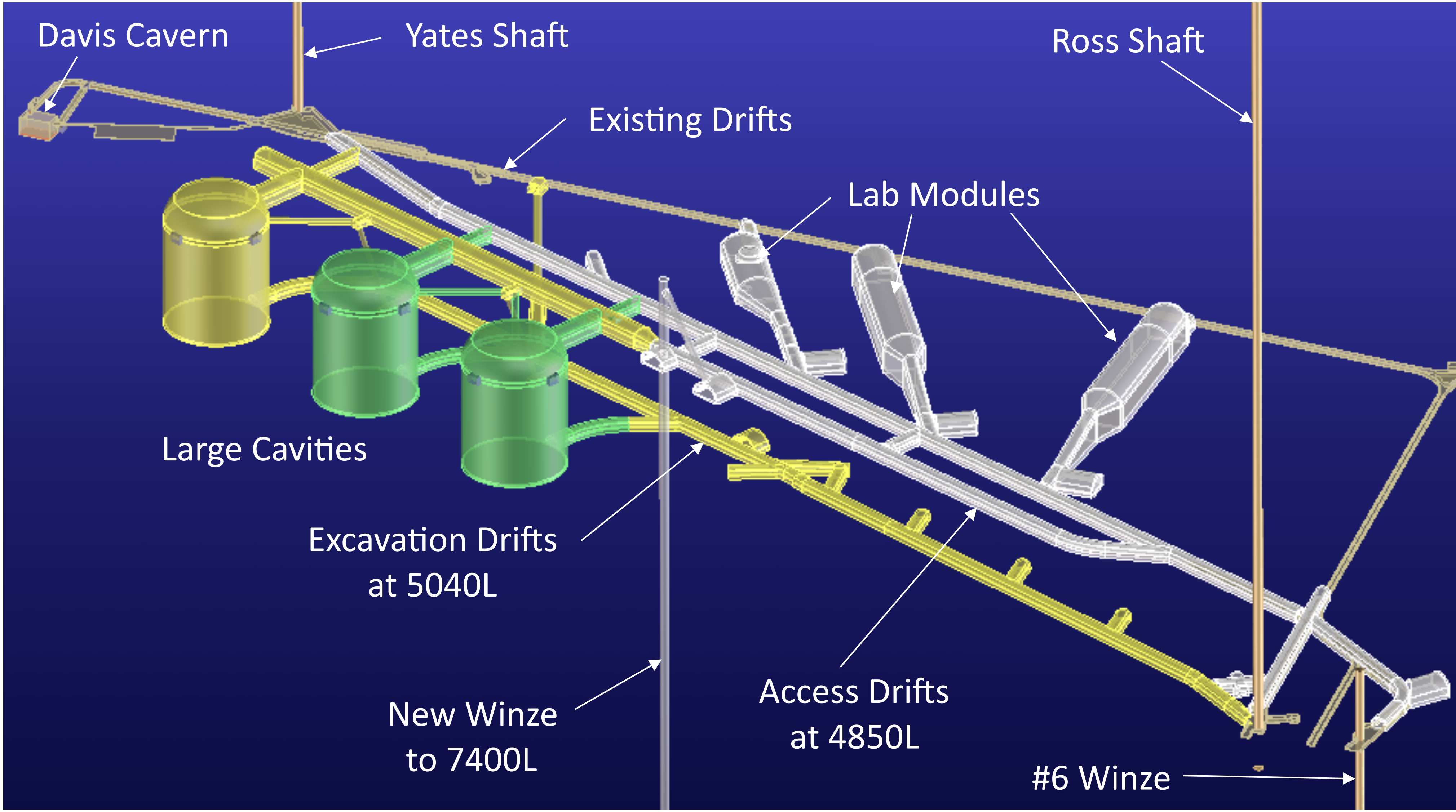


700 kW beam, on axis, water/argon megadetector, beamline to “DUSEL”

1300 km of matter: sign of matter effects ⇔ normal/inverted;

5 years of $\nu_\mu \mathrm{s}, \bar{\nu}_\mu \mathrm{s}$ running $\nu_\mu \to \nu_e$ vs $\bar{\nu}_\mu \to \bar{\nu}_e$ for $\not{C}$P

sounds like a good plan...



Davis Cavern
Yates Shaft
Ross Shaft
Existing Drifts
Lab Modules
Large Cavities
Excavation Drifts
at 5040L
New Winze
to 7400L
Access Drifts
at 4850L
#6 Winze

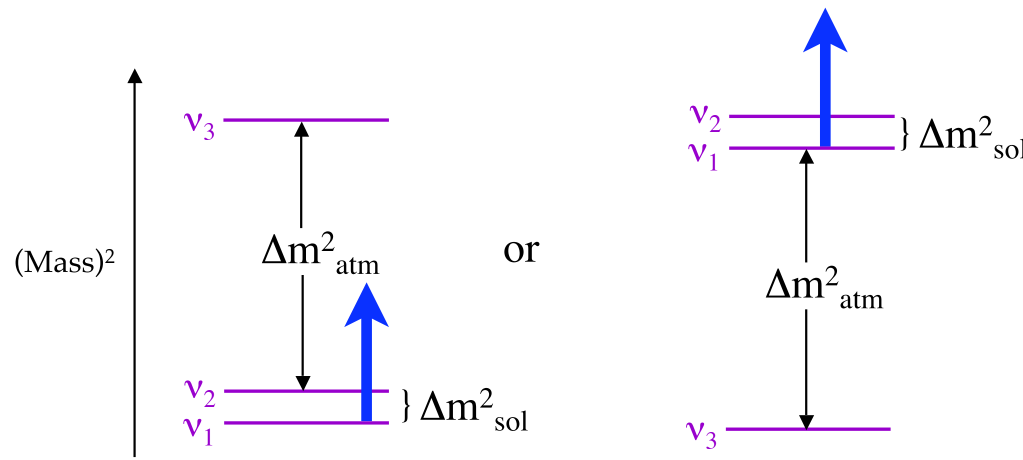
Vacuum formula

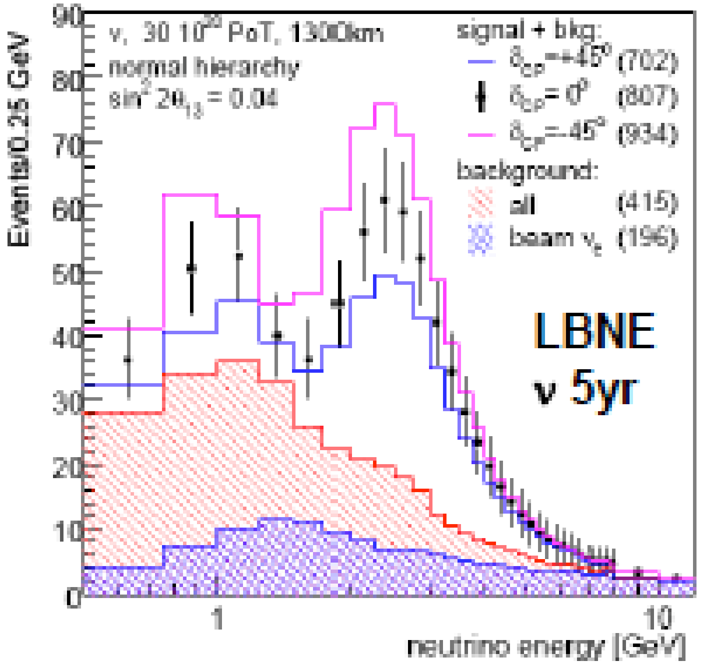
$$P\begin{pmatrix} \nu_\mu \rightarrow \nu_e \\ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \end{pmatrix} = \begin{array}{c} (\sin^2 2\theta_{23} \sin^2 2\theta_{13})(\sin^2 \Delta_{31}) \\ \pm \sin\delta \; (\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12})(\sin^2 \Delta_{31} \sin \Delta_{21}) \\ + \cos\delta \; (\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12})(\sin \Delta_{31} \cos \Delta_{31} \sin \Delta_{21}) \\ +(\cos^2 \theta_{23} \sin^2 2\theta_{12})(\sin^2 \Delta_{21}) \end{array}$$

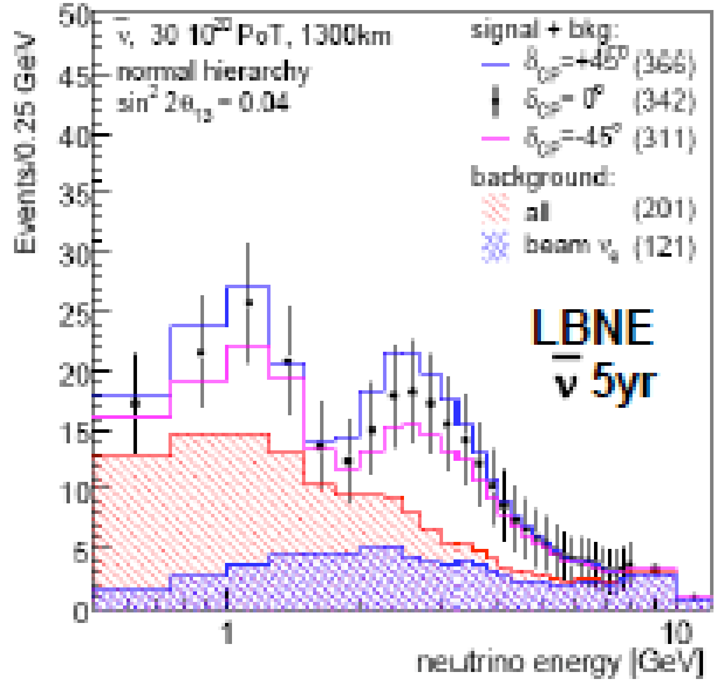
altered by matter

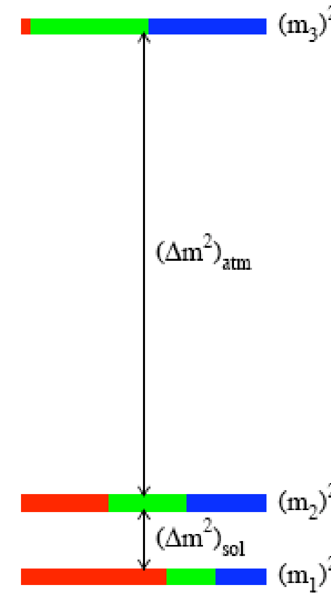
nonzero?

Effects intertwined, as two channels are not CP conjugate when in matter









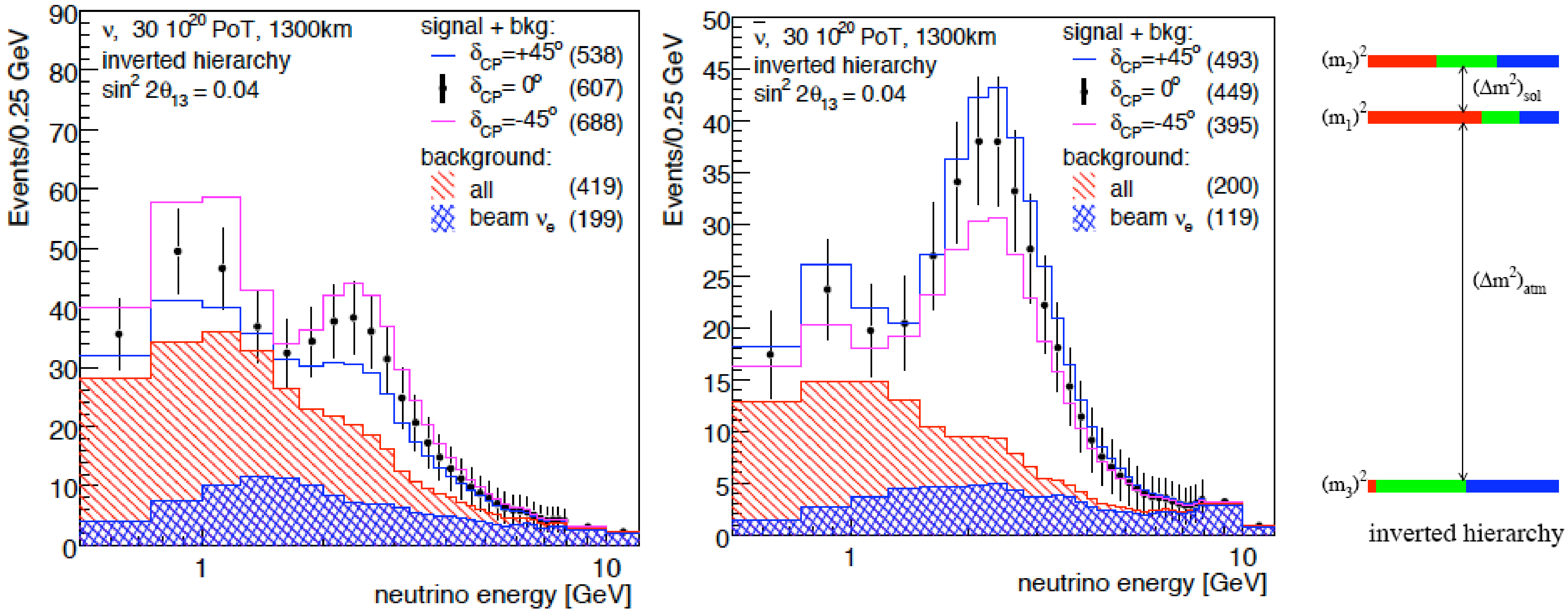
normal hierarchy

challenging:

broad band beam; baseline requires a spectrum centered at about 2 GeV

low statistics, some beam contamination, backgrounds from π^0 production

must be able to identify events (quasielastic kinematics) for which one can reconstruct the initial beam energy


ν, 30 10^20 PoT, 1300km
inverted hierarchy
sin^2 2θ13 = 0.04
signal + bkg:
δCP=+45° (538)
δCP= 0° (607)
δCP=-45° (688)
background:
all (419)
beam νe (199)
Events/0.25 GeV
neutrino energy [GeV]
ν̄, 30 10^20 PoT, 1300km
inverted hierarchy
sin^2 2θ13 = 0.04
signal + bkg:
δCP=+45° (493)
δCP= 0° (449)
δCP=-45° (395)
background:
all (200)
beam νe (119)
Events/0.25 GeV
neutrino energy [GeV]
(m2)^2
(Δm^2)sol
(m1)^2
(Δm^2)atm
(m3)^2
inverted hierarchy

So my conclusions

We have two “must do” decadal experimental programs -- ββ decay and LBNE -- addressing some of the most important questions in physics

Concerned that we won’t “get after it” the way we should

Especially important to do the LBNE program as well as possible
- -- as a nuclear physicist, complexity of the nuclear response at 2 GeV worries me: so many ways unobserved energy can be dissipated
- -- this argues for the most capable detector technology and the best near detector, and careful thought about ancillary tests one can make of event generators
- -- programs like Daedalus, with lower energy νs, deserve consideration

Not a time to cut corners